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A New Combined Framework for the Cellular Manufacturing Systems Design

Faouzi Masmoudi, Wafik Hachicha, Mohamed Haddar

Abstract— Cellular Manufacturing (CM) system has been recognized as an efficient and effective way to improve productivity in a factory. In recent years, there have been continuous research efforts to study different facet of CM system. The literature does not contain much published research on CM design which includes all design aspects. In this paper we provide a framework for the complete CM system design. It combines Axiomatic Design (AD) and Experimental Design (ED) to generate several feasible and potentially profitable designs. The AD approach is used as the basis for establishing a systematic CM systems design structure. ED has been a very useful tool to design and analyze complicated industrial design problems. AD helps secure valid input-factors to the ED. An element of the proposed framework is desmontrate through a numerical example for cell formation with alternative process.

Keywords: Cellular manufacturing, Design methodology Axiomatic Design, Experimental Design.

1 Introduction

Companies have ever been confronted with the question of development. In the face of competition, the ever more rapid emergence of news products, changing consumer fashions and globalisation, they are forced to call into question the efficiency of their design methods to keep their competitive edge and to turn their attention to such critical issues as productivity, quality and reducing manufacturing costs. In fact, there have been major shifts in the design of manufacturing systems using innovative concepts. The adoption of cellular manufacturing (CM) has consistently formed a central element of many of these efforts and has received considerable interest from both practitioners and academicians.

The CM system which is based on the concept of group technology philosophy aims at increasing productivity and production efficiency by reducing throughput times, set-up times, work in process inventories and lot sizes. There are two fundamentals problems associated with CM: part-family formation and machine-cell formation. Part-family formation is to group parts with similar geometric characteristics or processing requirements to take advantage of their similarities for the design or manufacturing purpose. Machine-cell formation is to bring dissimilar machines together and dedicate them to the manufacture of one or more part families.

When a company decides to apply CM organization, there are three important decision-making activities involved: (1) cell formation by grouping parts into part families and machines into cells, (2) inter-cell layout, and (3) intra-cell layout. In recent years, there have been continuous research efforts to study different facets of CM system. Numerous CM design problems are difficult to solve due to the fact that many parameters may contribute to the problem. The internal relationships among these parameters are seldom fully understood. Engineers have difficulties finding out which parameters to focus on, and how changes in certain parameters affect the CM system performance.

Several research approaches are developed to satisfy only one or limited functional requirements of the CM system design. The literature does not contain much published research on CM design which includes all design aspects. In this context, Silveira (1999) provides a logic sequential approach based on the integration of concepts and techniques. However, this approach is mostly based on the past experience and lacks detailed principles for implementation. Cabrera-Rios et al. (2002) proposes to use simulation, regression analysis, Taguchi method and a profit model under economic considerations. Kulak et al. (2005) propose the application of axiomatic design (AD) principles. His approach provides a methodology for transforming a process oriented manufacturing facility into a CM system.

The aim of this paper is to propose a global methodology for designing a CM system. The novelty of the proposed framework consists on combining AD principles with ED technique to generate several feasible and potentially profitable designs. In fact, the remainder of this paper is organized as follows: the next section provides the remainder of the related literature review. Section 3 presents the application of AD principles for CM design. Section 4 presents the DE integration method. An element of the proposed framework is desmontrate in section 5 through a numerical example for a cell formation with alternative process. Finally, section 6 provides conclusions of our work.

2 Related literature review

This subsection is organized as follows. First, the keys concepts of AD are presented. Second, a summary literature review of the use of AD in the design is provided. Finally, the principles of DE are presented.

2.1 Keys concepts of Axiomatic Design

In industrial practice, engineers tend to tackle a complex problem by decomposing it into sub-problems and attempting to maintain independent solutions for these smaller problems. This calls for an effective method that provides guidelines for the decomposition of complex problems and independent mappings between problems and

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solutions. AD developed by Suh (Suh, 1990) offers such a good decomposition mechanism.

AD defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through mapping between Functional Requirements (FRs) and Design Parameters (DPs). The FRs represents the goals of the design or *what* we want to achieve. FRs are defined in the functional domain in order to satisfy the needs which are defined in the customer domain. The DPs express how to satisfy the FRs. DPs are created in the physical domain to satisfy the FRs. The design domains are shown in Fig. 1.

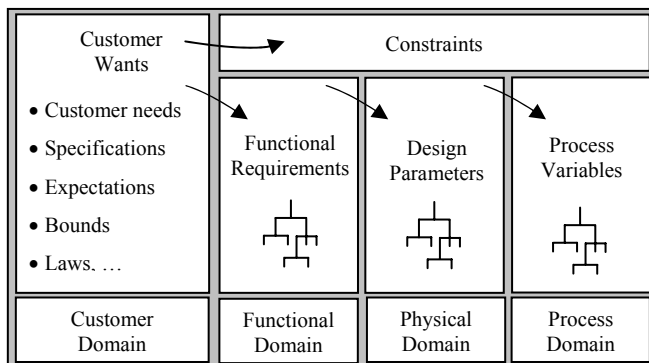


Fig.1. Relationship between design domains (Suh, 1990)

The customer domain is where the customer needs reside. These needs must be mapped to the functional domain where the customer needs are translated into a set of FRs, which by definition, are independent. Not only will Functional Requirements be defined for the new design, but also constraints will appear as a result of translating customer wants to FRs. Constraints have to be obeyed during the entire design process. They refer to FRs, as well as to DPs and process variables (PVs). This fact is indicated in Fig. 1 by placing the constraints above the functional, physical and process domain. The FRs are then mapped to the physical domain and the DPs are mapped to the process domain in terms of PVs.

The main goal of AD is to establish a scientific basis for design and to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools (Suh, 2001). In accomplishing this goal, the AD provides a systematic search process through the design space to minimize the random search process and determine the best design solution among many alternatives. The most important concept in AD is the existence of the design axioms. The first design axiom is known as the Independence Axiom and the second axiom is known as the Information axiom. They are formally defined (Suh, 1990) as follows:

Axiom 1: The Independence Axiom

In an acceptable design, the mapping between FRs and DPs is such that each requirement can be satisfied without affecting any other requirements. Mathematically, the relationship between the FRs and DPs are expressed as

$$(\text{FR}) = [A] (\text{DP}) \quad (1)$$

where

(FR) is the Functional Requirement vector

(DP) is the Design Parameter vector, and

$[A]$ is the design matrix that characterizes the design.

In general each A_{ij} of $[A]$ relates the i th FR to the j th DP. In order to satisfy the Independence Axiom, the design matrix must be either diagonal or triangular so that the relationships among FRs and DPs can be either uncoupled or decoupled which are claimed as good or acceptable design in AD. An uncoupled design (most preferred), the design matrix is a diagonal matrix indicating the independence of FR-DP pairs. Therefore, each FR can be satisfied by simply considering DP. In the decoupled design, the design matrix is a triangular matrix. Therefore the FRs can be answered systematically FR₁ to FR_n by only considering the first n DPs. This design appears most frequently in real life. That is why; we applied decoupled design in this present work. Finally, a coupled design matrix is not recommended by AD because much iteration will be involved in the design process.

Axiom 2: The information Axiom

Minimize the information content of the design. Among all proposed solutions that satisfy Independence Axiom, the best design has the minimum information content.

The axiomatic approach to design consists of the following key concepts (Gebala and Suh, 1992):

- The design world consists of distinct domains, such as the “consumer”, “functional”, “physical” and “process” domains.
- The design process involves mapping between the domains.
- Each domain is defined (or characterized) by a characteristic vector, which can be decomposed by zig-zagging between functional domain and physical domain. The physical solutions (i. e. DPs) should be found before decomposing the corresponding FRs at the same level in the hierarchy. That is, the entire FR hierarchy cannot be constructed without referring to the DP hierarchy at each corresponding level.
- The mapping process involves creative conceptualization, which must satisfy the design axioms: the Independence Axiom (Axiom 1) and the Information Axiom (Axiom 2).

The first axiom facilitates concurrent design without interactions. The second axiom is a variation of the old adage “keep it simple”. They represent two quality characteristics of the design.

2.2 The use of Axiomatic Design

Due to its usefulness of basic principles for analyzing, comparing, and selecting solutions, AD has been applied in different design fields such as manufacturing system process improvement, materials, software, organization and systems. Many AD applications have appeared in the literature in the last 15 years. Suh has introduced AD theory and principles first time (Suh, 1990). Then, he has applied AD approach in various domains such as artificial skin design (Gebala & Suh, 1992) and structural design in civil engineering structures (Albano & Suh, 1992). (Kim et al. 1991) have proposed an AD-based model for a software system design. FRs are the outputs of a software and DPs are the key inputs

to the software which can characterize or control the FRs. (Babic, 1999) provides a decision support system for arrangement of flexible manufacturing systems. (Chen et al. 2001) proposed a knowledge-based decision support system using independence axiom of AD and simulation analysis in order to improve cell performance. (Houshmand & Jamshidnezhad, 2002) provides a lean manufacturing based production system design using AD methodology. (Kulak et al. 2005) propose a framework and a road map to transform traditional production system from process orientation to cellular orientation, based on AD principles. This framework consists in a cellular manufacturing system design through AD theory. All of these studies have convincingly show the applicability and benefits of AD in solving industrial problems. Sure enough, since AD provides the independent mapping between each set of FR and its corresponding DP, it would help relieve the burden of system development processes.

2.3 The Experimental Design

A wide variety of approaches, methods, and analysis techniques, known collectively as experimental design, has been around for many decades. ED is a systematic approach to investigation of a system or process. A series of structured tests are designed in which planned changes are made to the input variables of a process or system. The effects of these changes on a pre-defined output are then assessed. ED has been a very useful tool to design and analyze complicated industrial design problems. It helps us to understand system characteristics and to investigate how inputs affect responses based on statistical backgrounds. In addition, it has been used to systematically determine the optimal system parameters with fewer testing trials (Montgomery, 1990).

One frequently used way of getting information about how different parameters (i.e DPs) in a process are related to one another, and to the performance measure of interest, is to use ED. It can be carried out in many different ways such as presented by many research. Box et al. (1978) developed the Design Of Experiments method. Taguchi (1987) proposed the robust design which finds the combination of control factors that has the lowest variation across the combinations of noise factors. These methods assume a set of given factors that may affect the performance measure of interest. Once the possibly important factors are selected, the ED finds the active factors, optimum factor values for product performance, or factor settings for variance minimization.

In the field of ED, statistical researchers have put much effort into how best to identify factors that are actively affecting the performance measure, one the best is carried out. Introducing domain knowledge when evaluating the experimental results has been found effective in selecting factors that are active (Engelhard, 2000). However, even though the selection of active factors from those incorporated in the ED can be quite accurate, a poorly defined input to an ED nevertheless yields a weak result. Thus, it is crucial to incorporate as much domain specific engineering knowledge as possible when selecting the parameters for the ED (Hamada and Wu, 1992).

The ED approach can be divided into a full factorial design and a fractional factorial design. The full factorial design has the advantages that all kinds of main effects and

interactions can be considered. However, since all combinations are to be tested, the number of experiments increases exponentially.

3. Axiomatic Design application

In what follows we present our FR-DP decomposition which based on framework provided by (Kulak et al., 2005). The proposed decomposition pass in five steps.

Step 1 consists in designing CM system is to define the Functional Requirements (FRs) of the system at the highest level of its hierarchy in the functional domain. At this stage, many FRs may be established. Each FR established at this stage may lead to a completely different CM design. In this present work, the following has been selected as the highest FR.

FR = Group parts and machines for simple material flow and provide customized production

Step 2 consists in mapping of FRs in the Physical Domain. Design parameters (DPs), which satisfy the FRs established in the previous step, are selected through a mapping process between the functional domain and the physical domain. In order to make the correct DP selection, the DP set corresponding to the FR set established before, must be exhaustively generated. The following DP has been selected to satisfy the FR provided above.

DP = Procedure for grouping all necessary machines into cells and parts into families

Step 3 consists in decomposing FR in the Functional Domain- Zigzagging between the domains. If the DPs proposed for satisfying the FRs defined in steps above can not be implemented without further clarification, the AD principles recommends returning to the functional domain for decomposing the FRs into their lower functional requirement set. The following lower functional requirements set is defined for decomposing the FR determined in the first step above.

FR1 = Determine alternative process plan for producing each part

FR2 = Cell formation based on incidence matrix

FR3 = Determine the number of each machine types and their suitable layouts and improve manufacturing cell throughput

Step 4 consists to find the corresponding DP's by mapping FR's in the physical domain. In satisfying the three FRs defined above, we move to the physical domain from the functional domain. The following DPs are in response the FRs listed as follows.

DP1 = Machine-Part incidence matrix with alternative process plan

DP2 = Parts/machines clustering techniques

DP3 = Manufacturing Shop data and requisite performance criteria

Step 5 consists in determining the corresponding Design Matrix (DM), which provides the relationships between the FR and DP elements. It is necessary to insure that the DM as established satisfies the axioms of AD principles (Suh, 2001). The DM set is as follows.

$$\begin{pmatrix} \text{FR1} \\ \text{FR2} \\ \text{FR3} \end{pmatrix} = \begin{bmatrix} \text{X} & & \\ \text{X} & \text{X} & \\ \text{X} & \text{X} & \text{X} \end{bmatrix} \cdot \begin{pmatrix} \text{DP1} \\ \text{DP2} \\ \text{DP3} \end{pmatrix} \quad (2)$$

In the DM above, the symbol X represents a strong relationship between the corresponding FR-DP pair. This DM presents a decoupled design, and thus, satisfies the independence axiom of the AD approach. It is an acceptable design because DPs can be performed sequentially.

The Functional Requirement FR3 (determine the number of each machine types and their suitable layouts and improve manufacturing cell throughput) as defined above may be decomposed with DP3 (Production data and requisite performance criteria) in mind as:

FR31 = Determine the capacity (or number of machines) needed of each machine type

FR32 = Group the individual machines into cells

FR33 = Eliminate or deal with remaining EE

The corresponding DPs may be stated as

DP31 = Production data

DP32 = Layout configuration

DP33 = EE-elimination strategies

The FRs and DPs developed for designing CM systems are summarized in Fig. 2, FRs and DPs are indented every time a design decomposition occurs to show the decomposition to lower levels of FRs and DPs. In this paper, an “end FR-DP” is by definition, an indecomposable FR-DP pair. Fig. 2 presents five “end FR-DP” which are FR1-DP1, FR2-DP2, FR31-DP31, FR32-DP32 and FR33-DP33.

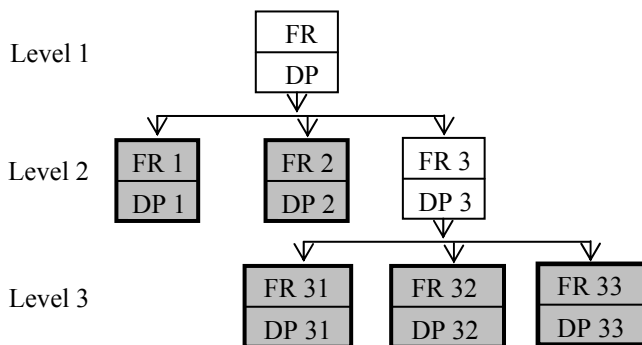


Fig. 2 Tree diagram for FRs and DPs

4. Experimental Design integration

An iterative method shown in Fig. 3 illustrates the proposed combination between AD and ED. There are two cases. The first consists of only one possible configuration and consequently ED is not necessary. On the other hand, the second case requires ED application.

4.1 The single-configuration case

Among “end FR-DP” of this case are FR2-DP2 (cell formation based on incidence matrix)-(Parts/machines clustering techniques) and FR31-DP31 (Determine the capacity needed of each machine type)-(Production data).

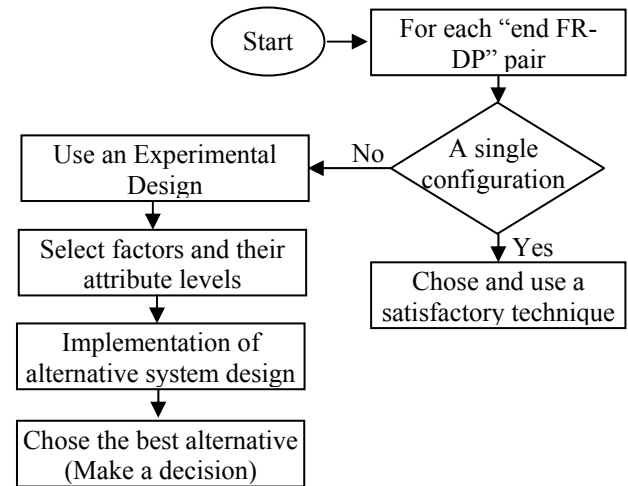


Fig. 3 The proposed procedure of DE

The first problem (FR2-DP2) is known in literature under the name cell formation problem. Extensive work has been performed in the area of this problem and numerous methods have been developed. The main used techniques are classification and coding systems, machine-component group analysis, mathematical and heuristic approaches, similarity coefficient based on clustering methods, graph-theoretic, knowledge-based and pattern recognition methods, fuzzy clustering methods, correlation analysis approaches, evolutionary and neural network approaches. Therefore, these numerous methods can be also classified into binary data based and production information. The binary data based problems consider only assignment information, that is, a part needs or needs not a machine to perform an operation. The assignment information is usually given in 0-1 incidence matrix (e.g. in King, 1980; Chan and Milner, 1982; Hachicha et al. 2007a and many others). The binary data based problems consider only a single objective in identifying cells. This ignores the fact that the CF problem, by structure, contains multiples objectives and limitations. To overcome these limitations, the production information based problems is based on the idea that necessary production data (such as production volumes, operation times, operation sequences, and others) should be incorporated in the early stages of the machine component grouping process (e.g. in Gupta and Saifoddini, 1990; Sarker and Balan, 1996; Hachicha et al. 2006 and others).

The second problem (FR31-DP31) is known in literature under the names “manufacturing cell sizing” (Masmoudi, 2006; Hachicha et al. 2007b) or “machine cell design” (Kamrani et al. 1998). In the literature, there are three basic types of models which are available to resolve this problem. These types are deterministic mathematical models, queuing models and computer simulation models. As far as we are aware, in general manufacturing system science, computer simulation, which can treat also complex systems, is arguably the most powerful of the three techniques (Chen et al. 2001).

4.3 The “many possible configurations” case

The others “end FR-DP” belong to this case are (FR1-DP1, FR32-DP32 and FR33-DP33). For each one, we propose to apply ED as the Fig. 3 indicates it. One of the principal goals of ED is to estimate how changes in input factors

affect the results, or responses, of the experiment. An ED dictates the number of possible configurations, the levels at which the factors must be set on each configuration, and the sequence in which these configurations must be performed. Once the factors and the correspondent levels are defined, it is possible to build a computer simulation model of the manufacturing system. The simulation model should allow the design team to easily experiment with the previously defined factors, as well as to compute statistics on specific aspects of interest. For the purposes of CM system, it is essential for the simulation model to keep statistics on machine utilization per machine, as well as average number waiting per machine, production, scrap, work-in-process inventory per part type, etc.

5. An illustrative example

This example addresses the FR1-DP1 pair which consists in (Determine alternative process plan for producing each part-Machine-Part incidence matrix with alternative process plan). In order to explain the methodology of the ED integration, a manufacturing system is considered with eight machines (labelled M1-M8) and six parts (labelled P1-P6). This example is provided by (Chan et al. 2005). The machine-part matrix with complete set of alternative process is shown in Table 1. The problem consists in selecting on process plan for each part will give the best grouping of the machines in cells.

Table 1
Machine-Part incidence matrix with alternative process plan

| Product | Route | M 1 | M 2 | M 3 | M 4 | M 5 | M 6 | M 7 | M 8 |
|---------|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| P1 | R11 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| | R12 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 |
| P2 | R20 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| P3 | R31 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| | R32 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| | R33 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |
| P4 | R40 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| P5 | R51 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | R52 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| P6 | R60 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |

Many experimental designs were carried out to investigate the effects of the alternative process for each part P1, P3 and P5 to grouping machines in cells. Part P1 at 2 levels (two alternatives routing: R11 and R12), part P3 at 3 levels (three alternatives routing: R31, R32 and R33) and part P5 at 2 levels (two alternatives routing: R51 and R52). A factorial design, as shown in Table 2, consists on twelve experiments (2 x 3 x 2 = 12).

Principal components analysis is an investigated of the data that is largely widespread among users in many areas of science and industry. It is one of the most common methods used by data analysts to provide a condensed description. Factor analysis is a dimension reduction technique which attempts to model the total variance of the original data set, via new uncorrelated variables called principal components. Principal components analysis consists in determining a small number of principal components that recover as much variability in the data as possible. These components are linear combinations of the original variables and account for

the total variance of the original data. Thus, the study of principal components can be considered as putting into statistical terms the usual developments of eigenvalues and eigenvectors for positive semi-definite matrices. The eigenvector equation where the terms $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_m$ are the real, nonnegative roots of the determinant polynomial of degree P given as:

$$\det(S - \lambda_i I) = 0 ; i \in \{1, m\} \quad (3)$$

where S: denote the incidence matrix and m: the number of machines.

When principal components analysis was performed on the mean centred data, a model with the first and the second principal components was usually obtained. This model explained the Cumulated Percentage (CP) of the variance in the data by the following expression:

$$CP = \frac{\lambda_1 + \lambda_2}{\sum_{k=1}^m \lambda_k} = \frac{\lambda_1 + \lambda_2}{m} \quad (4)$$

Detailed description of principal components analysis application in cell formation problem and CP calculation can be found in (Hachicha et al. 2006) and in (Hachicha et al. 2007a).

Table 2
Experimental design results

| Experiment | Process (P1, P3, P5) | CP |
|------------|------------------------|-------------|
| 1 | (R11, R31, R51) | 76.1 |
| 2 | (R11, R31, R52) | 85.6 |
| 3 | (R11, R32, R52) | 92.5 |
| 4 | (R11, R33, R52) | 85.6 |
| 5 | (R11, R32, R51) | 83.9 |
| 6 | (R11, R33, R51) | 76.1 |
| 7 | (R12, R31, R51) | 73.3 |
| 8 | (R12, R31, R52) | 80.2 |
| 9 | (R12, R32, R51) | 82.1 |
| 10 | (R12, R33, R51) | 69.1 |
| 11 | (R12, R33, R52) | 78.4 |
| 12 | (R12, R32, R52) | 91.6 |

The third experiment which indicated in Table 2 provides the best configuration. Sure enough, it gives the solution of cell formation with the minimum of intercellular movements. It corresponds to the maximum of CP (CP = 92.5 %). To assist also the interpretation of the results of the ED, the MIANITAB software was used. Fig. 4 represents the effects of each factors and Fig. 5 provides the importance of each interaction between the various factors.

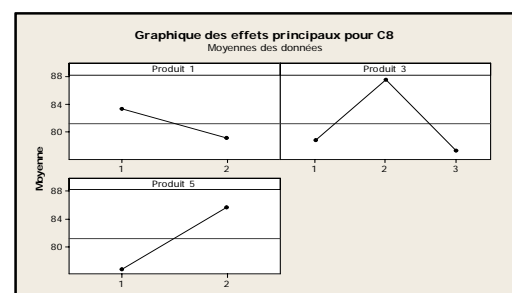


Fig. 4 The importance of effect

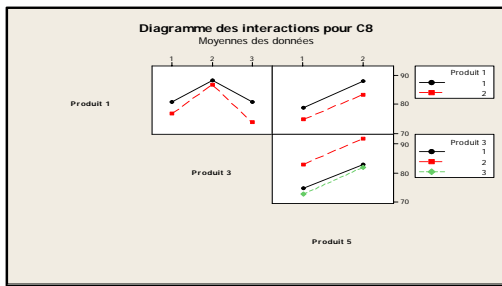


Fig. 5 The importance of interaction

The examination of Fig. 4 and Fig. 5 which should be taken account of the only effects of the parts P1 and P3, i.e. to retain the process R11 for the part P1 and the process R32 for the part P3. According to Fig 5, the part P5 is not bound by an interaction, its interpretation is thus immediate; it is enough to retain the process which gives the maximum of PC, i.e. the process R52. In this situation, it is to be noticed that the part P5 cannot be manufactured in the same cell as the parts P1 and P3

After having finished with FR1-DP1 class, i.e. selected for each part the best process, one passes to the following class which is FR-DP2 (cell formation solution). The FR2-DP2 can be easily determining by any of the numerous CF procedures which are proposed in literature.

Table 3

Final FR1-DP1 and FR2-DP2 solutions design

| Part | Route | M1 | M3 | M5 | M7 | M2 | M4 | M6 | M8 |
|------|------------|----|----|----|----|----|----|----|----|
| 1 | R11 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| 2 | R20 | 1 | 1 | 0 | 1 | | | | |
| 3 | R32 | 1 | 1 | 0 | 1 | | | | |
| 4 | R40 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| 5 | R52 | | | | | 1 | 1 | 1 | 1 |
| 6 | R60 | | | | | 1 | 1 | 1 | 1 |

The ED integration ensures in more the analysis of sensitivity. Indeed, Fig. 4 shows that the part P1 has the minimum of average effect. Consequently, the final cell formation solution is not very sensitive to a change of the part P1 process. The optimal solution is also more sensitive with a change of part P5 process than with a change of part P3 process.

6 Conclusion and future research

This paper provides a new framework for CM design which connects manufacturing system design objectives to operation design parameters. The proposed framework is carried out in two phases. The first phase is based on AD application. One of the most important advantages of AD is its hierarchical structure, which alleviate manufacturing design complexity. Basic requirements of a complete CM system design are categorized in five classes (FR-DP pair). The second phase consists in applying ED to each class.

The proposed framework is a logical and systematic approach to the design of CM systems, which makes it easily portable into practice. The ED integration has been demonstrated through a numerical example for the class of cell formation problem with alternatives process. Details and others real benefits of the application of the proposed framework into industrial cases study will be presented at our subsequent publications.

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